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(54) Title: OPTICAL WAVEGUIDE TERMINATION WITH VERTICAL AND HORIZONTAL MODE SHAPING
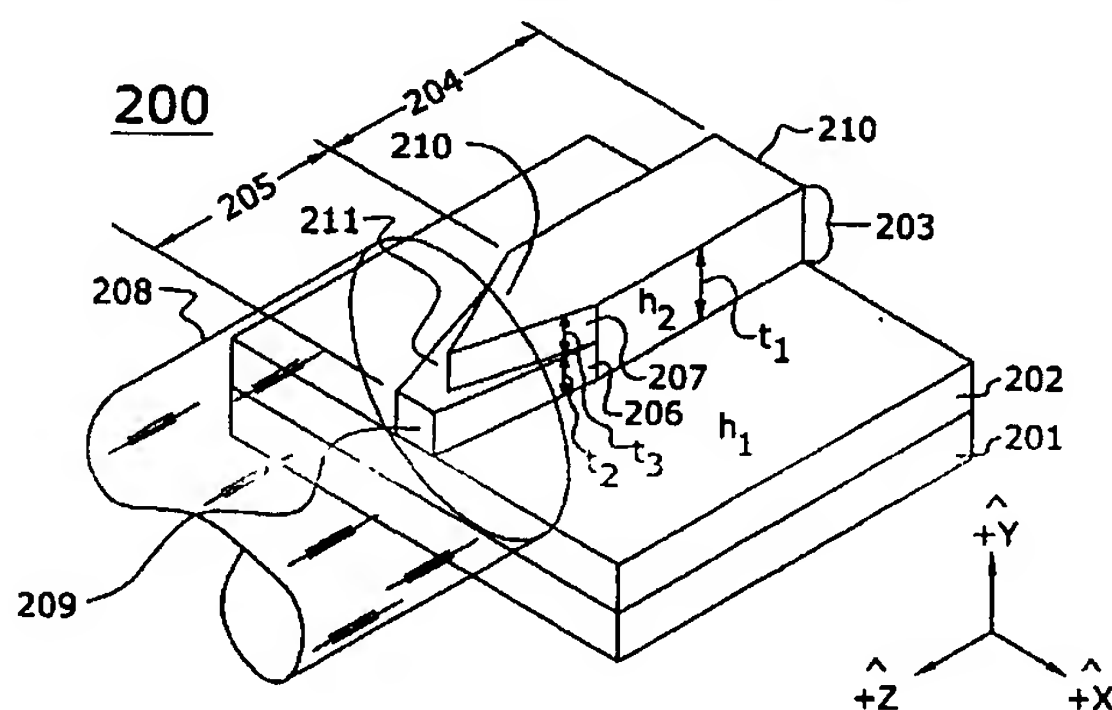
(57) Abstract: An optical device is disclosed which includes a waveguide that support a first optical mode in a first region and a second optical mode in a section region. The waveguide further includes single material guiding layer having a lower portion with a first taper and an upper portion with a second taper. Moreover, an optical device is disclosed which includes a waveguide having a single material guiding layer. The single material guiding layer a lower portion, which tapers from a first width to a second width, and an upper portion which tapers from the first width to a point.

OPTICAL WAVEGUIDE TERMINATION WITH VERTICAL
AND HORIZONTAL MODE SHAPING

Cross-Reference to Related Applications

The present application claims priority from U.S. Provisional Patent

Application Serial Number 60/255,868 filed December 14, 2000, entitled "Optical

Waveguide Termination With Vertical and Horizontal Mode Shaping.", and U.S.

Provisional Patent Application Serial Number 60/287,032 filed April 30, 2001,

entitled "Optical Waveguide Termination With Vertical and Horizontal Mode

Shaping." The disclosure of the above referenced provisional patent applications is

specifically incorporated by reference herein.

Field of the Invention

The present invention relates generally to optical integrated circuits (OIC), and

particularly to a structure for coupling optical waveguides.

Background of the Invention

Optical communications are evolving as the chosen technique for data and

voice communications. OIC's are often used at the point of transmission, reception

and amplification. Optical fibers may be coupled to the OIC to enable the optical

connection of the OIC other components of an optical communications system.

Typically, planar waveguides are used to efficiently couple light to and from active

and passive devices of the OIC. The planar waveguides are often made of relatively

high refractive index materials to facilitate desired integration and miniaturization of

the OIC. Coupling between the OIC and the optical communication system is often

achieved by coupling optical fibers of the system to planar waveguides of the OIC.

While clearly beneficial to the integration and miniaturization of OICs, the

planar waveguides commonly used in these circuits do not efficiently couple directly

to optical fibers. To this end, planar optical waveguides and optical fiber waveguides

used in high-speed and long-haul optical transmission systems often are designed to

support a single mode. Stated differently, the waveguides are designed such that the

wave equation has one discrete solution; although an infinite number of continuous

solutions (propagation constants) may be had. The discrete solution is that of a

confined mode, while the continuous solutions are those of radiation modes.

Because each waveguide will have a different discrete (eigenvalue) solution

for its confined mode, it is fair to say that two disparate waveguides, such as an

optical fiber and a planar waveguide, generally will not have the same solution for a

single confined mode. As such, in order to improve the efficiency of the optical

coupling, it is necessary to have a waveguide transition region between the planar

waveguide of the OIC and the optical fiber. This transition region ideally enables

adiabatic compression or expansion of the mode so that efficient coupling of the mode

from one type of waveguide to another can be carried out.

As mentioned, optical fibers typically support mode sizes (electromagnetic

field spatial distributions) that are much larger, both in the horizontal and vertical

directions than modes supported by in higher index waveguide structures, such as

planar waveguides. Therefore, a challenge is to provide a waveguide transition region

that enables adiabatic expansion of the mode so that it is supported by to the optical

fiber. Moreover, it is useful to achieve the adiabatic expansion of the mode in both

the horizontal and vertical directions.

Fabricating a waveguide to effect adiabatic expansion of the mode in the vertical direction has proven difficult using conventional fabrication techniques. To this end, tapering the thickness of the waveguide to affect the vertical adiabatic expansion of the mode is exceedingly difficult by conventional techniques.

What is needed therefore is a structure for effecting efficient coupling between waveguides having disparate characteristic mode sizes which overcomes the drawbacks of the prior art described above.

Summary of the Invention

According to an exemplary embodiment of the present invention an optical device is disclosed which includes a waveguide that supports a first optical mode in a first region and a second optical mode in a second region. The waveguide further includes single material guiding layer having a lower portion with a first taper and an upper portion with a second taper.

According to another exemplary embodiment of the present invention, an optical device is disclosed which includes a waveguide having a single material guiding layer. The single material guiding layer has a lower portion, which tapers from a first width to a second width, and an upper portion which tapers from the first width to a point.

Brief Description of the Drawings

In the following detailed description, for purposes of explanation and not limitation, exemplary embodiments disclosing specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be apparent to one having ordinary skill in the art having had the benefit of the present

disclosure, that the present invention may be practiced in other embodiments that depart from the specific details disclosed herein. Moreover, descriptions of well-known devices, methods and materials may be omitted so as to not obscure the description of the present invention.

Fig. 1(a) is a top view of a waveguide according to an illustrative embodiment of the present invention.

Fig. 1(b) is a perspective view of the waveguide shown in Fig. 1(a).

Fig. 1(c) is a cross-sectional view along line 1(c)-1(c) of Fig. 1(a) of a waveguide according to an illustrative embodiment of the present invention.

Fig. 2(a) is a perspective view of a waveguide coupled to an optical fiber in accordance with an illustrative embodiment of the present invention.

Fig. 2(b) is a top view of a waveguide according to an illustrative embodiment of the present invention.

Figs. 3(a)-3(f) are graphical representations of the electric field distributions of optical modes at various regions of a waveguide according to an illustrative embodiment of the present invention.

Figs. 4(a)-4(d) are top views of guiding layers of waveguides in accordance with illustrative embodiments of the present invention.

Fig. 5 is a perspective view of an illustrative embodiment of the present invention.

Fig. 6 is a perspective view of an illustrative embodiment of the present invention.

Defined Terms:

1. As used herein, the term "on" may mean directly on or having one or more layers therebetween.

2. As used herein, the term "single material" includes materials having a substantially uniform stoichiometry. These materials may or may not be doped. Illustrative materials include, but are in no way limited to silicon, SiO_xN_y, SiO_x, Si_3N_4, and InP. Moreover, as used herein, the term single material includes nanocomposite materials, organic glass materials.

3. As used herein, the term "bisect" may mean to divide into two equal parts. Alternatively, the term "bisect" may mean to divide into two unequal parts.

Detailed Description

In the following detailed description, for purposes of explanation and not limitation, exemplary embodiments disclosing specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be apparent to one having ordinary skill in the art having had the benefit of the present disclosure, that the present invention may be practiced in other embodiments that depart from the specific details disclosed herein. Moreover, descriptions of well-known devices, methods and materials may be omitted so as to not obscure the description of the present invention.

Briefly, the present invention relates to an optical waveguide which fosters adiabatic mode expansion/compression thereby enabling optical coupling between a first waveguide, which supports a first optical mode and a second waveguide, which supports a second optical mode. According to an exemplary embodiment, the waveguide supports a first optical mode in a first region and a second optical mode in

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a second region. The waveguide includes a single material guiding layer having a

lower portion with a first taper and an upper portion with a second taper. According

to another exemplary embodiment of the present invention, an optical device is

disclosed which includes a waveguide having a single material guiding layer. The

single material guiding layer has a lower portion, which tapers from a first width to a

second width, and an upper portion which tapers from the first width to a point. The

single material may be disposed on a stress compensating layer, which is used to

reduce stress induced polarization mode dispersion and temperature induced

polarization mode dispersion. This stress compensating layer will not substantially

impact the optical characteristics of a waveguide.

The waveguide according to exemplary embodiments described herein may be

an integral part of an OIC, formed during the fabrication of the OIC. The waveguide

illustratively couples a planar waveguide of the OIC to an optical fiber of an optical

communications system. Of course, multiple waveguides may be used to couple

multiple optical fibers at various locations of the OIC.

Fig. 1(a) and 1(b) show a waveguide 100 according to an illustrative

embodiment of the present invention. A guiding layer 101 is disposed on a lower

cladding layer 102. The guiding layer 101 is illustratively a single material. An

upper cladding layer (not shown) covers the guiding layer 101. The indices of

refraction of the upper and lower cladding layers may or may not be the same. In all

cases, the indices of refraction of the upper and lower cladding layers are less than the

index of refraction (n_g) of the guiding layer 101. The waveguide 100 includes a first

region 103 and a second region 104. The guiding layer 101 further includes an upper

portion 105 and a lower portion 106. The upper portion 105 tapers at an angle θ_2

relative to the edge 107 of the guiding layer 101. The lower portion 106 tapers at an angle θ_1 relative to the edge 107 of the guiding layer 101.

Reducing the thickness and width of the guiding layer 101 effects substantially adiabatic expansion/compression of an optical mode traversing the waveguide. (As would be readily apparent to one having ordinary skill in the art, adiabatic expansion of a mode occurs when the mode is traveling in the +z-direction; while from the reciprocity principle of optics, adiabatic compression occurs when the mode is traveling in the -z-direction). As the width of the guiding layer 101 reduces along a first taper 108 from a width w_1 to effectively zero width at termination point 109, the effective index of refraction is reduced. Moreover, the guiding layer 101 reduces along second taper 111 from a width w_1 to a width w_2, a finite width, at endface 110. Again, the effective index of refraction decreases as the width of the guiding layer 101 decreases. Due to the reduction in the effective index of refraction, the horizontal portion of the optical mode expands (is less confined in the guiding layer 101) as the mode traverses the waveguide in +z-direction. Fabrication of the first taper 108 and second taper 111 of the guiding layer 101 may be carried out by well known techniques, as described in further detail below.

Of course, it is also useful to adiabatically expand/compress the vertical portion of the optical mode. In order that the vertical portion of the optical mode undergoes substantially adiabatic expansion/compression, the thickness of the guiding layer is reduced.

Turning to Fig. 1(c), a cross-sectional view of an illustrative embodiment along the lines 1b-1b of Fig. 1(a) is shown. In this embodiment, the thickness of guiding layer 101 reduces in the +z-direction from a thickness t_1 to a thickness t_2 as shown. An upper cladding layer (not shown) may cover the guiding layer 101. While

the single material used for guiding layer 101 has an index of refraction n_g, as the thickness of the guiding layer 101 is reduced from a thickness t_1 to a thickness t_2, the effective index of refraction is reduced. Accordingly, the vertical portion of an optical mode traversing the guiding layer 101 in the +z-direction will expand, as it is less confined to the guiding layer 101. Finally, according to the illustrative embodiment of the present invention shown in Figs. 1(a) and 1(b), the endface 110 of the guiding layer 101 has a width w_2, thickness t_2 and index of refraction that produce an optical mode well matched to that of an optical fiber. Accordingly, the single optical mode supported by the waveguide 100 at endface 110 will also will be one which is supported by an optical fiber. As such, good optical coupling between the guiding layer 101 of the waveguide 100 and the guiding layer 101 of an optical fiber (not shown) results.

The waveguide 100 according to exemplary embodiments of the present invention may be fabricated so that the upper portion and lower portion of the guiding layer 101 are symmetric about a plane which longitudinally bisects the guiding layer 101. Alternatively, the waveguide 100 according to exemplary embodiments of the present invention may be fabricated so that the upper portion, or the upper portion and the lower portion, of the guiding layer 101 are asymmetric about an axis which bisects the waveguide 100. These and other exemplary embodiments of the present invention are described in the examples described below.

Example I

Turning to Fig. 2(a), a perspective view of a waveguide 200 according to an exemplary embodiment of the present invention is shown. A lower cladding layer 202 is disposed on a substrate 201. A guiding layer 203 is disposed on lower cladding

layer 202. Waveguide 200 has a first region 204 and a second region 205. The guiding layer 203 includes a lower portion 206 and an upper portion 207. An optical mode is coupled from an endface 209 to an optical fiber 208. For the purposes _f ease of discussion, an upper cladding layer is not shown in Fig. 2(a). This upper cladding layer would cover the guiding layer 203. The upper cladding layer, guiding layer 203 and lower cladding layer 202 form a waveguide 200 according to an illustrative embodiment of the present invention. The upper cladding layer may have the same index of refraction as the lower cladding layer 202. Alternatively, the upper cladding layer may have a higher (or lower) index of refraction as the lower cladding layer 202. The guiding layer 203 has an index of refraction, n_g, which is greater than the indices of refraction of both the upper cladding layer and lower cladding layer 202. Finally, according to the illustrative embodiment of the present example of the invention, the upper portion 207 and lower portion 206 are symmetric about an axis 210 that bisects guiding layer 200 (shown below).

As mentioned above, it may be desirable to couple optical fiber 208 to an OIC (not shown). This coupling may be achieved by coupling the optical fiber to a planar waveguide (not shown) of the OIC. However, the planar waveguide supports a first optical mode and the optical fiber 208 supports a second optical mode. As such, the first optical mode of the planar waveguide will not be supported by the optical fiber in an efficient manner, and a significant portion of the energy of the first optical mode of the planar waveguide could be transformed into radiation modes in the optical fiber 208.

Waveguide 200 may be disposed between the planar waveguide of the OIC and the optical fiber 208 to facilitate efficient optical coupling therebetween. To this end, as described in detail above, the first optical mode of the planar waveguide is

physically more confined to the guiding layer of the planar waveguide than the second optical mode is in the guiding layer of the optical fiber. That is, the confined mode of the planar optical waveguide is smaller than the confined mode of an optical fiber. Accordingly, waveguide 200 is useful in efficiently transferring the energy of the first optical mode of the planar waveguide into optical fiber 208 by a substantially adiabatic expansion of the mode. Stated differently, the solution to the wave equation for the planar waveguide is a first optical mode. As the supported mode of the planar waveguide traverses the waveguide 200 it undergoes a transformation to a second optical mode that is supported by a cylindrical optical waveguide (optical fiber 208).

Advantageously, the transformation of the mode which is supported by the planar waveguide, to a mode which is supported by waveguide 200; and ultimately to a mode which is supported by optical fiber 208, is substantially an adiabatic transformation. As such, transition losses from the planar waveguide to the optical fiber 208 are minimal. Illustratively, transition losses are approximately 0.1% or less. Moreover, the second region 205 of the waveguide 200 effects both horizontal and vertical transformation of the mode. Finally, the above discussion is drawn to the adiabatic expansion of a mode in waveguide 203. Of course, from the principle of reciprocity in optics, a mode traveling from optical fiber 208 (-z-direction) to a planar waveguide would undergo an adiabatic compression by identical physics.

Fig. 2(b) shows a top-view of the waveguide 200 of Fig. 2(a). The guiding layer 203 of waveguide 200 includes a first region 204 which is coupled to (or is a part of) another waveguide, such as a planar waveguide (not shown). The second region 205 is the region in which the transformation of the mode supported in the planar waveguide into one which is supported by another waveguide (e.g. optical fiber 208) occurs. This second region 205 includes a lower portion 206 and an upper

portion 207. Upon reaching the end face 209, the single confined mode is one which

is supported by optical fiber 208. Accordingly, a significant proportion of the energy

of the mode is not lost to radiation modes in the optical fiber. In summary, the

structure of the illustrative embodiment of Fig. 2(a) and Fig. 2(b) results in efficient

coupling of both the horizontal portion and the vertical portion of the optical mode.

The structure is readily manufacturable by standard semiconductor fabrication

techniques.

As shown is Fig. 2(b), as the guiding layer 203 tapers, the lower portion 206 is

at a first angle, θ_1, relative to the edge of waveguide 203; and the upper portion 207 is

at a second angle, θ_2, again relative to the edge of waveguide 203. Illustratively, the

angles are in the range of approximately $0°$ to approximately $0.5°$. Sometimes, it is

preferable that the angles are in the range of greater than $0°$ to approximately $0.5°$.

As can be readily appreciated by one having ordinary skill in the art, the greater the

angle of the taper, the shorter the length of the taper. Contrastingly, the smaller the

taper angle, the longer the length of the taper. As will be described in greater detail

herein, a greater taper length may require more chip area, which can be

disadvantageous from an integration perspective, but may result in a more adiabatic

transformation (expansion/compression) of the mode. Ultimately, this may reduce

transition losses and radiation modes in the second region 205 of the waveguide and

the optical fiber 208, respectively. Finally, it is of interest to note that angle θ_1 and

the angle θ_2 are not necessarily equal. Illustratively, the angle θ_2 is greater than angle

θ_1.

The length of taper of lower portion 206 (shown in Fig. 2(b) as L_2) is on the

order of approximately $100 \mu m$ to approximately $1,500 \mu m$. Of course, Fig. 2(b) is

not drawn to scale as the width of the waveguide (shown as w_a) is hundreds of times

smaller than the length L_2 of the taper portion (e.g. 1-10 microns wide). The length of the taper of the upper portion 207 of the waveguide (shown at L_1) is on the order of approximately 100 μm to approximately 1,500 μm. As described above, smaller taper angles will result in longer taper lengths (L_1) and consequently may require more chip surface area, which can be less desirable in highly integrated structures. However, the length of the taper (L_1) also dictates the efficiency of the mode shaping. To this end, longer tapers may provide more efficient mode shaping because the mode transformation is more adiabatic.

In the illustrative embodiment of Figs. 2(a) and 2(b), the upper portion 207 and the lower portion 206 of guiding layer 203 are substantially symmetric about an axis 210 that bisects the guiding layer 203. As such, the first angle θ_1 of the lower portion is the same on both sides of the axis 210. Similarly, second angle θ_2 of upper portion is the same on both sides of the axis 210. In the present embodiment in which the upper portion 207 and lower portion 206 are symmetric about axis 210, the lengths L_1 and L_2 are the same on both sides of the axis 210.

Finally, as described below, the tapering of the waveguide reduces the width (w_g) of the guiding layer 203, which enables substantially adiabatic expansion/compression of the horizontal portion of the mode. At the endface 209, the width is reduced to a width w_g as shown. Illustratively, this width w_g is in the range of approximately 0.5 μm to approximately 2.0 μm. While the embodiment shows that guiding layer 203 terminates at this width rather abruptly. Of course, as in the illustrative embodiment of Figs. 1(a) and 1(b), it is possible to continue the guiding layer 203 at the reduced width, w_g, for a finite length, which ultimately terminates at an endface.

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Fabrication of the waveguide 200 may be effected by relatively standard semiconductor fabrication process technology. Particularly advantageous is the fact that the guiding layer 203 may be fabricated of a single layer, illustratively a single layer of a single material. To fabricate the device shown illustratively in Fig. 1, a suitable material is deposited on the substrate 201. This material is illustratively monolithic, and is deposited in a single deposition step. A conventional photolithographic step is thereafter carried out, and a conventional etch, such as a reactive ion etching (RIE) technique may be carried out to form the waveguide 203 and to define the lower portion 206. The upper portion 207 may be fabricated by a second conventional photolithography/etch sequence.

Alternatively, a monolithic material may be deposited on layer 202, and in the deposition step, the taper in the lower portion 206 of second region 205 may be formed. After the deposition step, the guiding layer 203 may be partially etched to form the taper in the top portion 207. The top portion 207 can be etched by standard dry or wet etch techniques, both isotropically and anisotropically. While the illustrative embodiment described thus far is drawn to the guiding layer 203 being formed of a single layer, it is clear that this waveguide may be formed of multiple layers of a single material as well. To this end, the guiding layer 203 may be comprised of a lower layer which includes the lower portion 206 and an upper layer (not shown) which includes the upper portion 207. In the technique in which two sequential layers are deposited, the top layer is thereafter etched by standard technique to form the taper in the top portion 207 of the second region 205 of the guiding layer 203.

For purposes of illustration, and not limitation, in the illustrative embodiment, the lower cladding layer is silicon dioxide (SiO_2) having an index of refraction on the order of approximately 1.46. The guiding layer is illustratively silicon oxynitride (SiO_xN_y), and the upper cladding layer (not shown) is also SiO_2. In this illustrative example of materials, in the first region 204, guiding layer 203 has thickness (shown at t_1 in Fig. 2(a)) on the order of approximately $2.0 \mu m$ to approximately $4.0 \mu m$. As can be seen in Fig. 2(a), the thickness of guiding layer 203 reduces from t_1 to t_2. Moreover, as can be seen in Fig. 2(a), at section 210 guiding layer 203 has a thickness t_1, which is the sum of the thickness t_3 of upper portion 207 and thickness t_2 lower portion 206. At section 211, the thickness of guiding layer 203 is reduced to t_2, which is the thickness of lower portion 206.

While the taper (reduction of the width, w_g) of the upper portion 207 and lower portion 206 results in the adiabatic expansion of the horizontal portion of the confined mode, the reduction in the thickness from t_1 to t_2 results in the adiabatic expansion of the vertical portion of the confined mode. As described above, the reduction of the thickness of the guiding layer 203 results in a reduction in the effective index of refraction (n_{eff}) for the vertical portion of the mode. As such, the mode is less confined vertically in the guiding layer 203, and is progressively expanded as it traverses the waveguide 200 in the +z-direction. At endface 209, the mode is effectively matched to the guiding layer characteristics of optical fiber 208. The lower portion 206 has an illustrative thickness (t_2) in the range of approximately $1.0 \mu m$ to approximately $2.0 \mu m$. Finally, the upper portion 207 illustratively has a thickness (t_3) in the range of approximately $1.0 \mu m$ to approximately $2.0 \mu m$.

Figs. 3(a) and 3(b) show the electric field distribution of the confined mode in the first portion 204 of waveguide 200 along the x-axis at a point z_0 and along the y-axis at point z_0, respectively. Stated differently Fig. 3(a) shows the horizontal portion of the electric field of the confined mode in first region 204, while Fig. 3(b) shows the vertical portion of the electric field of the mode. As can be appreciated, the mode energy is particularly confined in the first region 204 of the waveguide 200. Characteristically, this is an energy distribution of a supported eigenmode of a planar waveguide (not shown), which is readily coupled to the first region 204 of waveguide 200 having virtually the same physical characteristics as the planar waveguide.

Figures 3(c) and 3(d) show the electric field of the confined mode in the second region 205 of the waveguide 200, particularly near point 212. More particularly, Figs. 3(c) and 3(d) show the horizontal and vertical portions of the electric field distribution of the confined mode, respectively, in second region 205 of waveguide 200. As can be seen, the supported mode in this portion of waveguide 200 is slightly expanded (less confined to the guiding layer 203) compared to the supported mode in the first portion 204.

Figs. 3(e) and 3(f) show the horizontal and vertical portion of the electric field distribution, respectively, of the confined mode at approximately endface 209 of the second region 205 of waveguide 200. At this point, the electric field distribution of the confined mode is significantly greater in both the horizontal direction (Fig. 3(e)) and the vertical direction (Fig. 3(f)). The adiabatic transformation of the mode from the relatively confined mode of the first region 204 to the relatively expanded mode at endface 209 is relatively adiabatic, and results in transition losses which are substantially negligible.

A review of Figs. 3(a) – 3(e) reveals the adiabatic expansion of the confined mode traversing the guiding layer 203 in the +z-direction. As referenced above, the tapers of the lower portion 206 and the upper portion 207 results in a reduction in the width, wg, of guiding layer 203. This results in a reduction in the effective index of refraction (n_{eff}) for the horizontal portion of the mode. As such, the horizontal portion of the mode is less confined to the guiding layer 203. Accordingly, the mode is expanded as it traverses the waveguide 200. Additionally, the reduction in the thickness of the guiding layer 203 from t_1 to t_2 results in a reduction in the effective index of refraction (n_{eff}) for the vertical portion of the mode. As such, the mode is less confined in the guiding layer 203. The mode as represented in Figs. 3(d) and 3(e) will be supported by an optical fiber.

Example II

As described above, the upper portion and lower portion of the guiding layer in Example I were substantially symmetric about an axis bisecting the guiding layer. In the illustrative embodiments of Example II, the upper portion of the guiding layer may be asymmetric about an axis bisecting the guiding layer. The lower portion may be symmetric about the axis bisecting the guiding layer. Alternatively, both the upper portion and the lower portion may be asymmetric about an axis bisecting the guiding layer. The asymmetry of either the upper portion of the guiding layer alone or of the upper and lower portions of the guiding layer about an axis which bisects the guiding layer may be beneficial from the perspective of manufacturing and fabrication.

In the illustrative embodiments described herein, the asymmetry of the taper of either the upper portion or the upper portion and lower portion of the guiding layer offers more tolerance during fabrication. To this end, mask positioning tolerances are

greater when fabricating tapers that are asymmetric. It is of interest to note that standard masking and etching steps described in connection with the illustrative embodiments in Example I may be used in fabricating the waveguides of the illustrative embodiments of the present example. Moreover, as described in connection to the illustrative embodiments of Example I, waveguides according to the illustrative embodiment facilitate efficient optical coupling between two waveguides by adiabatically expanding/compressing an optical mode. Again, waveguides according to the exemplary embodiments of Example II illustratively couple optical fibers of an optical communication system to planar waveguides of an OIC.

Turning to Fig. 4(a), a top view of guiding layer 401 of a waveguide shown. Again, a lower cladding layer (not shown) and an upper cladding layer (not shown) may be disposed under and over the guiding layer 401, respectively, thereby forming a waveguide. The upper and lower cladding layers are substantially the same as described in connection with the illustrative embodiments described fully above. A lower portion 402 of guiding layer 401 has a lower portion first taper 403 and a lower portion second taper 404. The lower portion first taper 403 is defined by an angle θ_3 and length 405. The length 405 of the lower portion first taper 403 is readily determined by dropping a perpendicular to the terminal point of the first taper 403. Lower portion second taper 404 is defined by an angle θ_4, a length 406, again defined by dropping a perpendicular to the terminal point. An upper portion 407 of guiding layer 401 is disposed on the lower portion 402. The upper portion 407 has an upper portion first taper 408 is defined by an angle θ_1 and a length 410, which may be found by dropping a perpendicular from the terminal point of upper portion first taper 408. Similarly, an upper portion second taper 409 of guiding layer 401 is defined by angle θ_2 and a length 411, which is determined by dropping a perpendicular from the

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terminal point of the taper to the edge of the guiding layer as shown. The guiding

layer 401 has an illustrative width w_g, which decreases to a width w_g at endface 410.

The section 411 of guiding layer 401 has a constant width w_g. Section 412 is

illustrative, and the endface having reduced width w_g may be located at the

termination of lower point 402.

In the illustrative embodiment of Fig. 4(a), an axis 413 bisects the guiding

layer 401. The upper portion 407 is asymmetric about the axis 413. Contrastingly,

the lower portion 402 is substantially symmetric about the axis 413. In the illustrative

embodiment of Fig. 4(a), the angles θ_1 and θ_3 are dissimilar, and the taper lengths 410

and 411 of tapers 408 and 409, respectively, are also dissimilar. However, in the

illustrative embodiment of Fig. 4(a), the angles θ_3 and θ_4 are substantially identical.

The lengths 405 and 406 of lower portion first and second tapers 403 and 404,

respectively, are substantially identical, as well. Advantageously, the constraints on

mask location tolerances in forming the upper portion 407 of guiding layer 401 are

lessened, when compared to the embodiments described above where the upper

portion is symmetric about an axis that bisects the guiding layer 407.

As can be readily appreciated, by varying angle θ_3 of upper portion first taper

403 and length 405 of lower portion first taper 403; by varying angle θ_4 of lower

portion second taper 404 and length 406 of lower portion second taper 404; by

varying angle θ_1 of upper portion first taper 408 and length 410 of upper portion first

taper 408; and by varying angle θ_2 of upper portion second taper 409 and length 411

of upper portion second taper 409, a variety of structures for guiding layer 401 may be

realized. The results may be that the upper portion is asymmetric about axis 413,

while the lower portion 402 is symmetric about axis 413. Alternatively, both upper

portion 407 and lower portion 402 of guiding layer 401 may be asymmetric about axis

400. Some illustrative structures are described below. Of course, these are merely exemplary and are in no way limiting of the present invention.

Turning to Fig. 4(b), a top view of an illustrative embodiment of the present invention is shown. In the illustrative embodiment of Fig. 4(b), the lower portion 402 of the guiding layer 401 is substantially symmetric about axis 413. That is, angle θ_3 is substantially identical to angle θ_4, and the length 405 is substantially the same as second length 406. However, angle θ_2 and length 411 are essentially zero. As such, there is no second taper of upper portion 407. Upper portion 407 is substantially defined by θ_1, and length 410. This embodiment is particularly advantageous in that a mask used to define the upper portion 407, need be only semi-self-aligning. That is it need only intersect the lower portion 402, since the taper of upper portion 407 is one-sided and terminates at a point at the edge of lower portion 402. This absence of a second taper results in a lower need for accuracy in mask alignment.

Turning to Fig. 4(c), another illustrative embodiment of the present invention is shown. Guiding layer 401 includes lower portion 402 and upper portion 407. In this illustrative embodiment, angles θ_1 and θ_4 are essentially zero. Upper portion 407 includes upper portion second taper 409 having a taper length 411. Lower portion 402 has a first taper 403 having a taper length 405.

According to this illustrative embodiment, both the upper portion 407 and the lower portion 402 are asymmetric about axis 413 that bisects the guiding layer 401.

Turning to Fig. 4(d), another illustrative embodiment of the present invention is shown. In this illustrative embodiment both the lower portion 402 and the upper portion 407 of the guiding layer 401 are asymmetric about an axis 413 that bisects the guiding layer 401. Again, angles θ_1 and θ_2, in conjunction with lengths 410 and 411,

may be used to define the taper of upper portion 407. Similarly, the angle θ_3 and length 405 may be used to define the taper of the lower portion 402 of guiding layer 401.

As can be readily appreciated from a review of the illustrative embodiments of Example II, the guiding layer may be of a variety of structures. The embodiments described are merely exemplary of the waveguide of the present invention. As such, these exemplary embodiments are intended to be illustrative and in no way limiting of the invention.

Example III

In the present example, other illustrative embodiments of the present invention are described. These illustrative embodiments may incorporate the principles of symmetry and asymmetry of the guiding layer as described above. Moreover, many of the fabrication techniques described in connection with the illustrative embodiments of Examples I and II may be used.

Fig. 5 shows a perspective view according to another illustrative embodiment of the present invention. A waveguide 500 includes a lower cladding layer 502. The lower cladding layer 502 may be disposed on a substrate. A guiding layer 503 is disposed on guiding layer 502. An upper cladding layer (not shown) may be disposed on the guiding layer 503. In the embodiment shown in Fig. 5, the bottom portion 507 of the guiding layer 503 is a diffused guiding layer. In the particular embodiment shown in Fig. 5, the lower portion 507 is illustratively a Ti:LiNbO$_3$ waveguide. The top portion 506 of waveguide 503 is a material having an index of refraction that is substantially the same as that of the lower portion 507 (the diffused waveguide). Advantageously, the embodiment shown in Fig. 5 is useful because diffused guiding

layers are often wider (along x axis) than they are deep (along y axis). The second region 505 of the top portion 506 is tapered in the manner similar to that shown in previous embodiments, for example that of Fig. 1. The top portion 506 of the second region 505 is useful in providing both vertical and horizontal mode transformation.

Turning to Fig. 6, another illustrative embodiment of the present invention is shown. In this illustrative embodiment waveguide 600 has a second region 605 that illustratively includes three layers. Of course, this is merely illustrative, and more layers are possible. The substrate 601 has a lower cladding layer 602 disposed thereon. The guiding layer 603 has a first region 604 and a second region 605. The second region 605 has a lower portion 606 and an intermediate portion 607 and a top portion 610. An upper cladding layer 611 (not shown) may be dispose over guiding layer 603. Again, a waveguide couples to the end face 608; and illustratively the waveguide is an optical fiber (not shown). In the illustrative embodiment shown in Fig. 6, the second region 605 is symmetric about an axis 609 which bisects the lower portion 606. The fabrication sequence and materials are substantially the same in the embodiment shown in Fig. 6. Of course, a third photolithography/etching step would have to be carried out in the embodiment in which one layer of material is deposited to form the guiding layer 603. Of course, multiple depositions of the same material could be carried out in a manner consistent with that described in connection with Fig. 1. Thereafter, a sequence of photolithographic and etching steps would be carried out to realize the lower portion 606, intermediate portion 607 and top portion 610 of the second region 605.

In the foregoing examples, waveguides have been described as being made with tapers that very in horizontal width, that is, width changes in the dirction of the plane of the substrate that the waveguide is fabricated on. This is an advantage of the

invention, for while waveguides with vertical taper could also be fabricated as an embodiment of the present invention, these much more difficult to manufacture.

The invention having been described in detail in connection through a discussion of exemplary embodiments, it is clear that various modifications of the invention will be apparent to one having ordinary skill in the art having had the benefit of the present disclosure. Such modifications and variations are included within the scope of the appended claims.

We Claim:

1. An optical device, comprising:

a single-mode waveguide which supports a first optical mode in a first region and a second optical mode in a second region, said waveguide including a single material guiding layer having a lower portion with a first taper and an upper portion with a second taper.

2. An optical device as recited in claim 1, wherein said first taper is at a first angle, and said second taper is at a second angle.

3. An optical device as recited in claim 1, wherein said single material guiding layer is a single layer.

4. An optical device as recited in claim1, wherein said second region terminates at an endface.

5. An optical device as recited in claim 4, wherein said single material guiding layer has a first width in said first region and a second width at said endface.

6. An optical device as recited in claim 4, wherein said single material guiding layer has a first thickness in said first region and a second thickness at said endface.

7. An optical device as recited in claim 1, wherein said single material guiding layer has a width and said width decreases from a first width to a second width.

8. An optical device as recited in claim1, wherein said single material guiding layer has a thickness and said thickness decreases from a first thickness to a second thickness.

9. A An optical device as recited in claim 1, wherein said guiding single material is chosen from the group consisting essentially of silicon, silicon oxynitride, SiO_2, Si_3N_4, and InP.

10. An optical device as recited in claim 1, wherein said first optical mode is more tightly confined than said second optical mode in said guiding layer.

11. An optical device as recited in claim 2, wherein said first angle is in the range of approximately 0° to approximately 0.5°.

12. An optical device as recited in claim 2, wherein said second angle is in the range of approximately 0° to approximately 0.5°.

13. An optical device as recited in claim 2, wherein said upper portion adiabatically transforms a vertical portion of said first optical mode.

14.   An optical device as recited in claim 6, wherein said first thickness is approximately 2.0 micrometers to approximately 4.0 micrometers, and said second thickness is approximately 1.0 micrometers to approximately 2.0 micrometers.

15.   An optical device as recited in claim 2, wherein said upper portion is symmetric about an axis which bisects said lower portion.

16.   An optical device as recited in claim 2, wherein said upper portion is asymmetric about an axis which bisects said lower portion.

17.   An optical device as recited in claim 1, wherein said single material guiding layer is a plurality of layers.

18.   An optical device as recited in claim 1, wherein said guiding layer further comprises:

        at intermediate portion having a third taper and being disposed between said lower portion and said upper portion.

19.   An optical device as recited in claim 1, wherein said second region terminates at an end face and said end face couples to another waveguide.

20.   An optical device as recited in claim 4, wherein said end face has a thickness of approximately 1.0 micrometers to approximately 2.0 micrometers.

21. An optical device as recited in claim 1, wherein said single material guiding layer is disposed on a stress compensating layer.

22. An optical device as recited in claim 1, wherein said waveguide couples a planar waveguide to an optical fiber.

23. An optical device as recited in claim 1, wherein said first region is coupled to another optical waveguide.

24. A waveguide as recited in claim 23, wherein said another waveguide is planar.

25. A waveguide as recited in claim 1, wherein said lower portion is a diffused guiding layer.

26. An optical device comprising:

A single-mode waveguide including a single material guiding layer having a lower portion which tapers from a first width to a second width, and an upper portion which tapers from said first width to a point.

27. An optical device as recited in claim 26, wherein said single material guiding layer has a thickness which decreases from a first thickness (t_1) to a second thickness (t_2).

28. An optical device as recited in claim 27, wherein said single material guiding layer further includes a guiding section having an endface, and said guiding section has said second width and said second thickness.

29. An optical device as recited in claim 26, wherein said lower portion tapers at a first angle and said upper portion tapers at a second angle.

30. An optical device as recited in claim 26, wherein said upper portion is symmetric about an axis that bisects said guiding layer.

31. An optical device as recited in claim 26, wherein said upper portion is asymmetric about an axis that bisects said guiding layer.

32. An optical device as recited in claim 31, wherein said lower portion is asymmetric about an axis that bisects said guiding layer.

33. An optical device as recited in claim 26, wherein said guiding single material is chosen from the group consisting essentially of silicon, silicon oxynitride, SiO_2, Si_3N_4 and InP.

34. An optical device as recited in claim 26, wherein said first angle is in the range of approximately 0° to approximately 0.5°.

35. An optical device as recited in claim 26, wherein said second angle is in the range of approximately 0° to approximately 0.5°.

36. An optical device as recited in claim 26, wherein said first width is in the range of approximately 1 micron to approximately 10 microns.

37. An optical device as recited in claim 26, wherein said second width is in the range of approximately 0.1 microns to approximately 10 microns.

38. An optical device as recited in claim 27, wherein said first thickness is in the range of approximately $2\mu m$ to approximately $4\mu m$.

39. An optical device as recited in claim 27, wherein said first thickness is in the range of approximately $1\mu m$ to approximately $2\mu m$.

40. An optical device, comprising:

a single-mode waveguide which supports a first optical mode in a first region and a second optical mode in a second region, said waveguide including a single material guiding layer having a lower portion with a first taper and an upper portion with a second taper, wherein the first taper of the lower portion consists essentially of a horizontal taper, and wherein the second taper of the upper portion consists essentially of a horizontal taper.

41. An optical device comprising:

A single-mode waveguide including a single material guiding layer having a lower portion which tapers horizontally from a first width to a second width, the lower portion having at least one edge, and an upper portion which tapers horizontally from said first width to a point terminating on an edge of the lower portion.

100

FIG. 1 (a)

FIG. 1 (b)

FIG. 1 (c)

200

FIG. 2 (a)

200
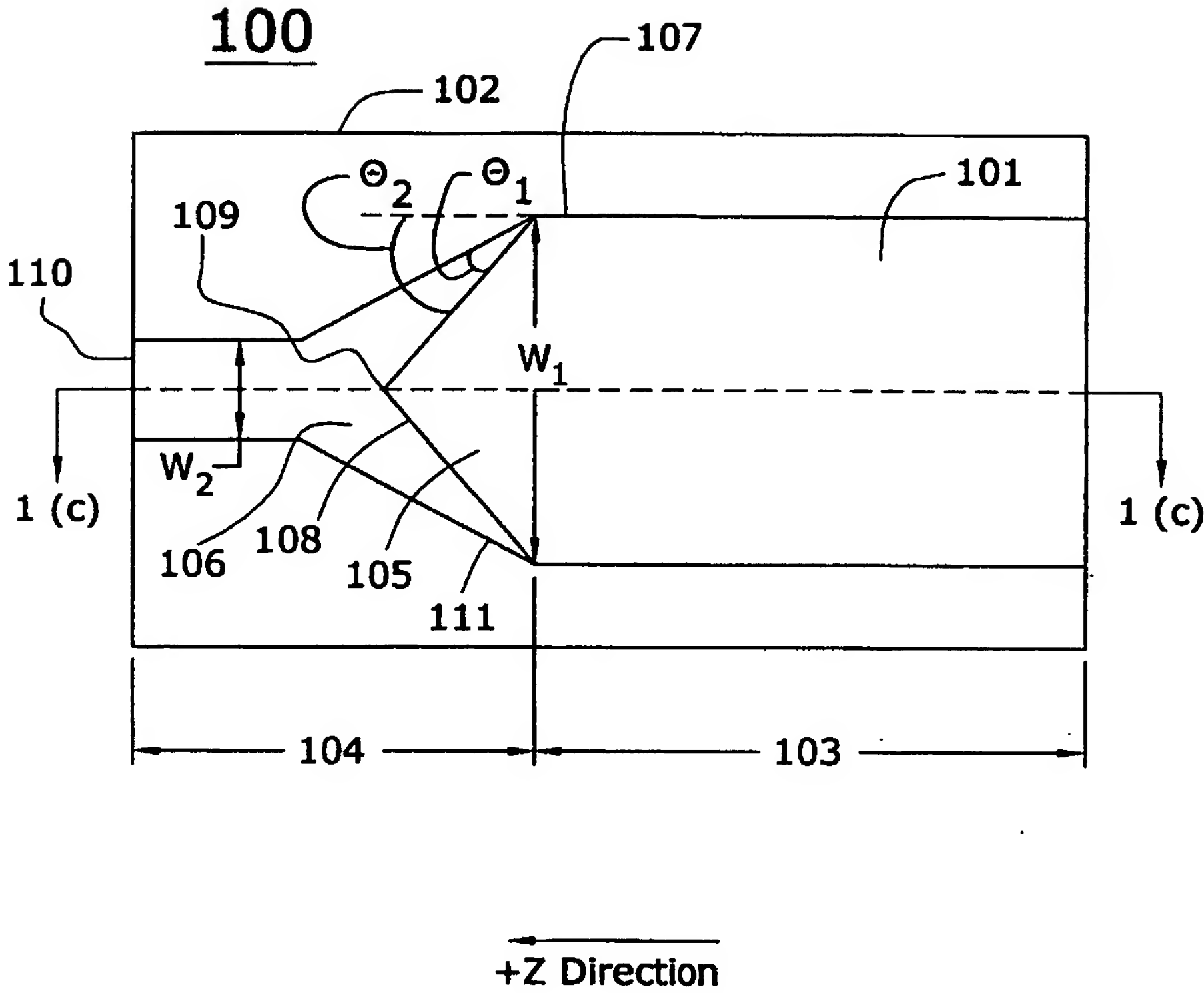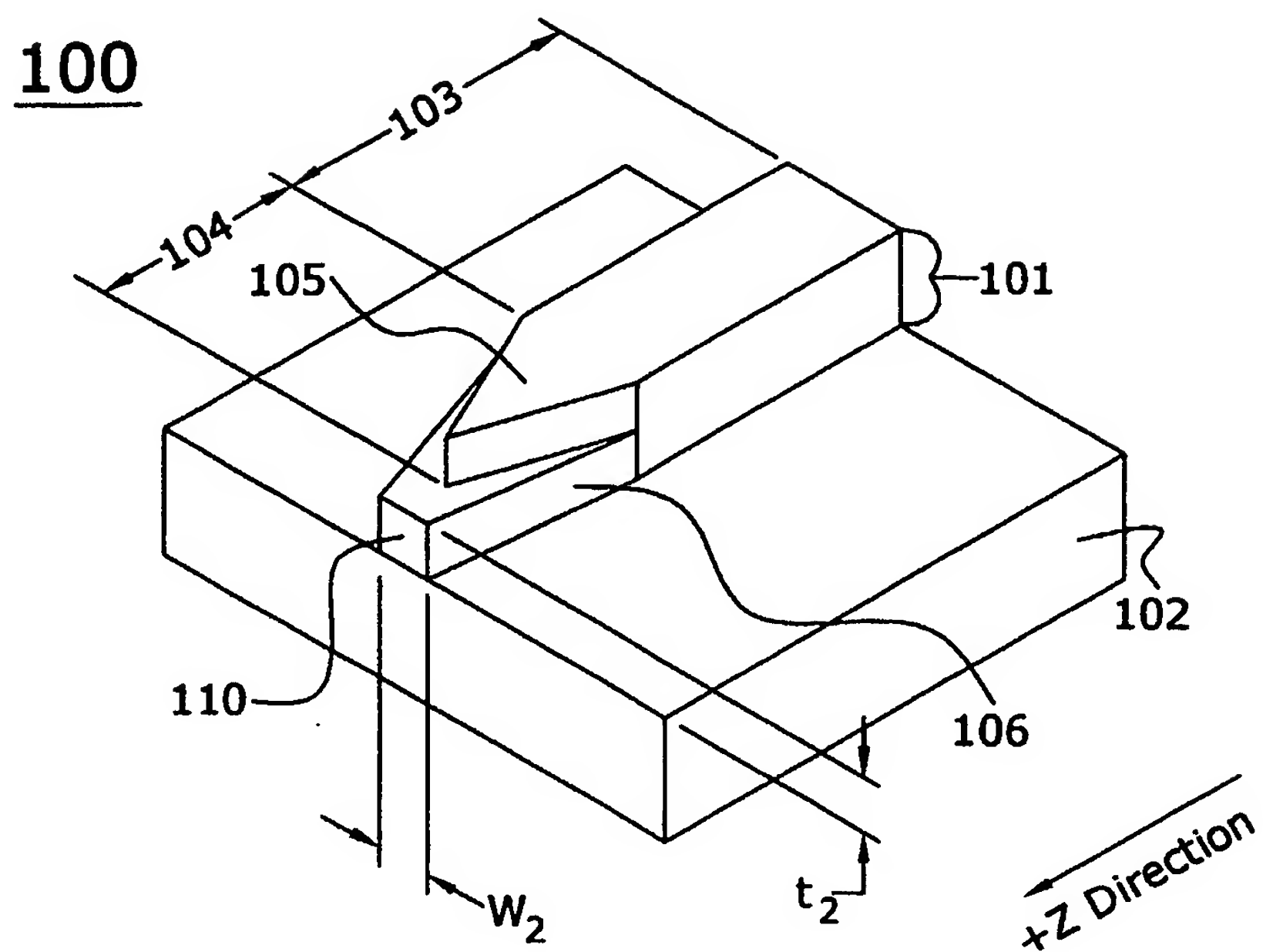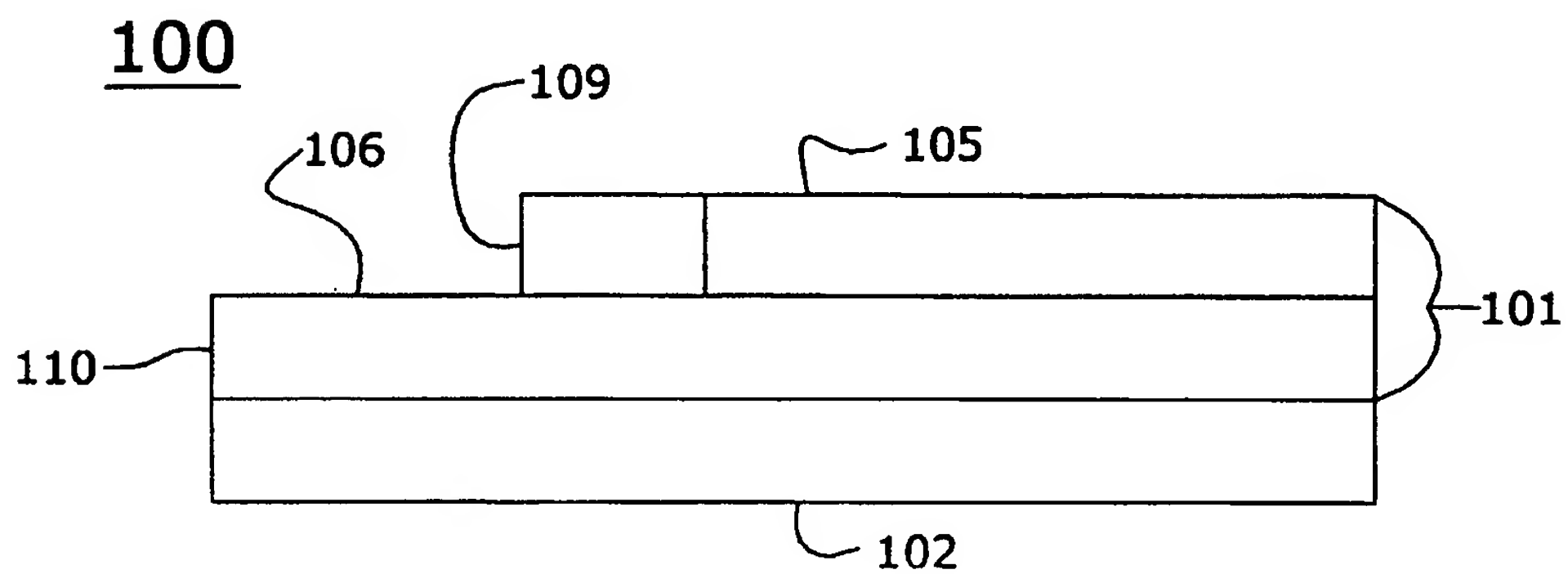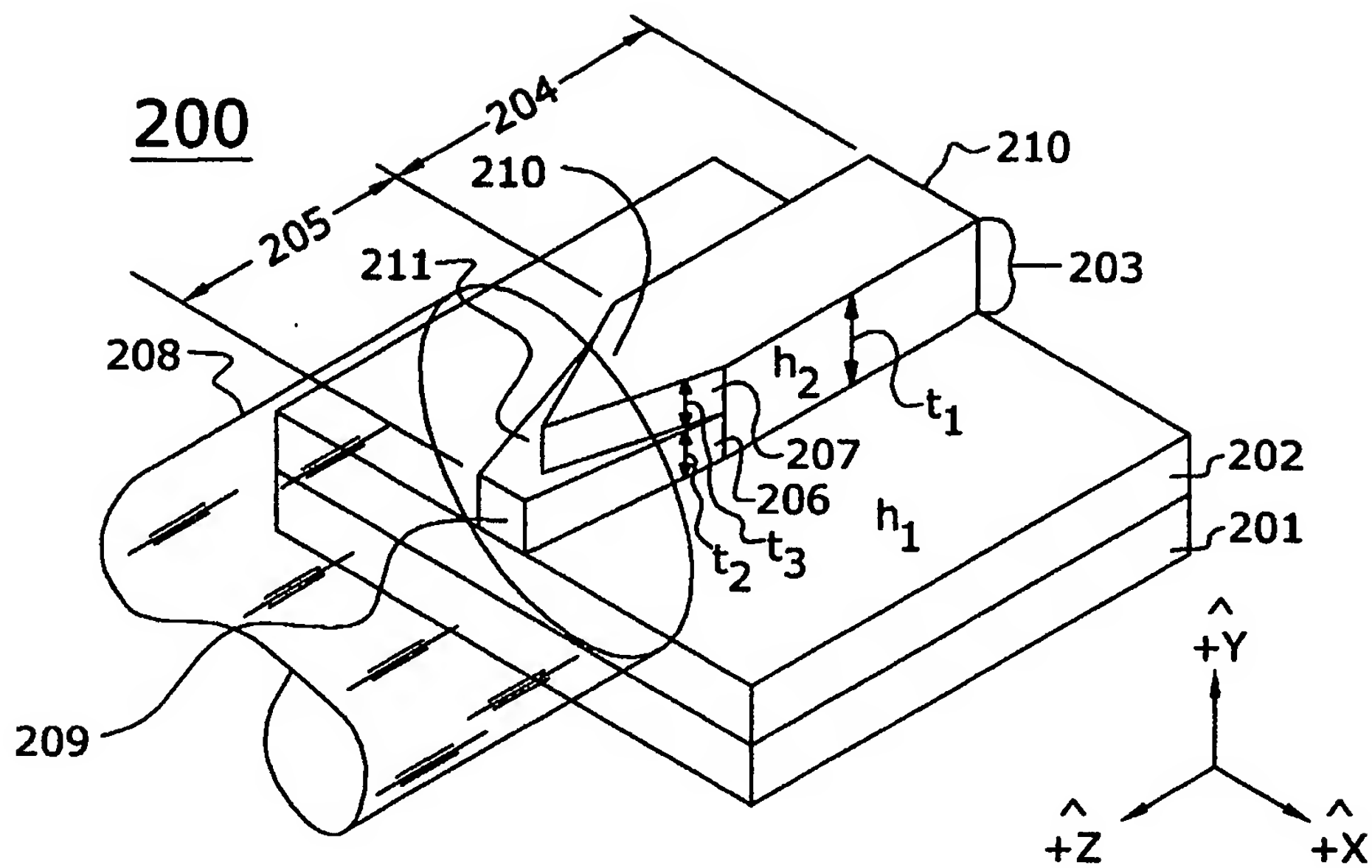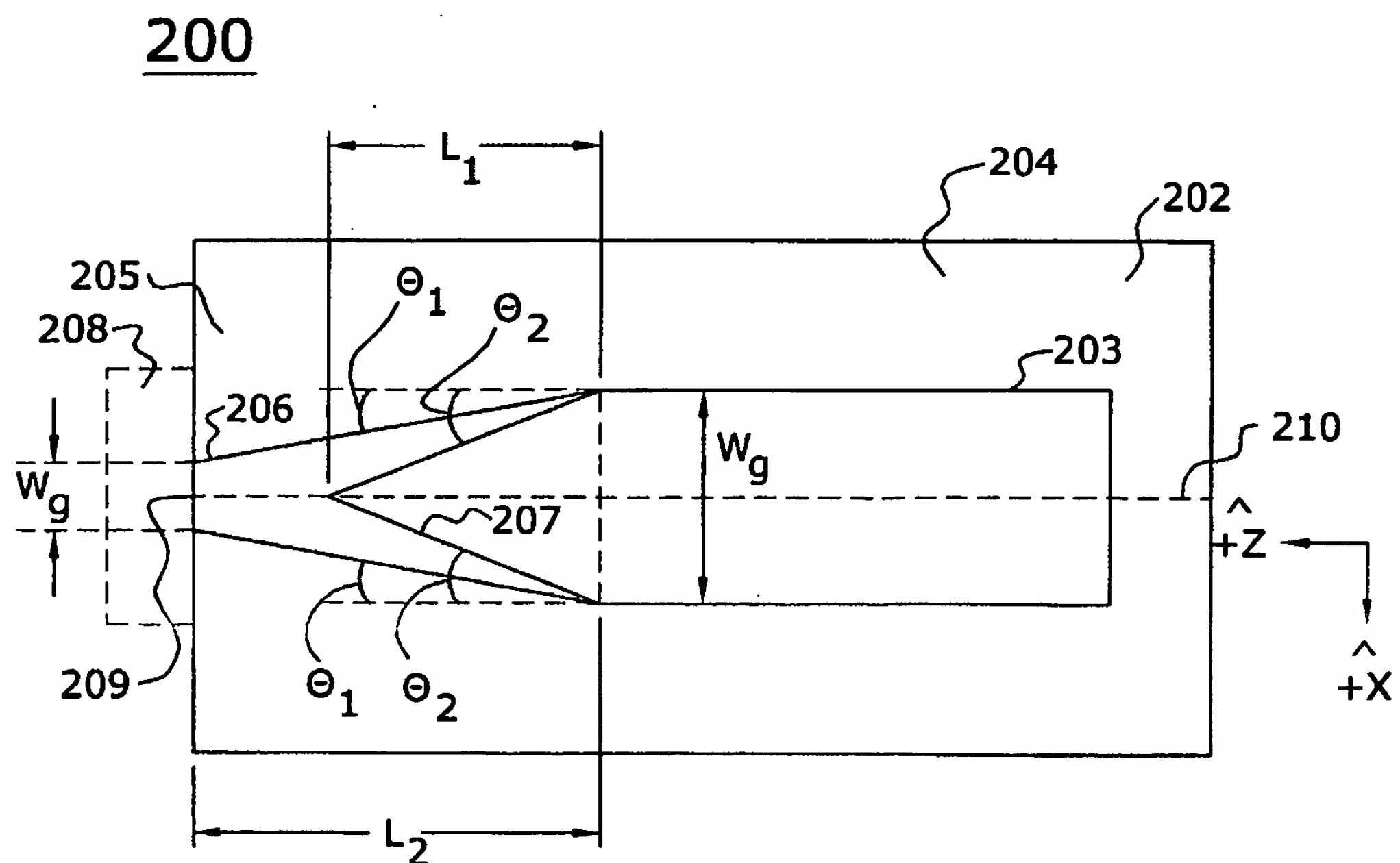
FIG. 2 (b)
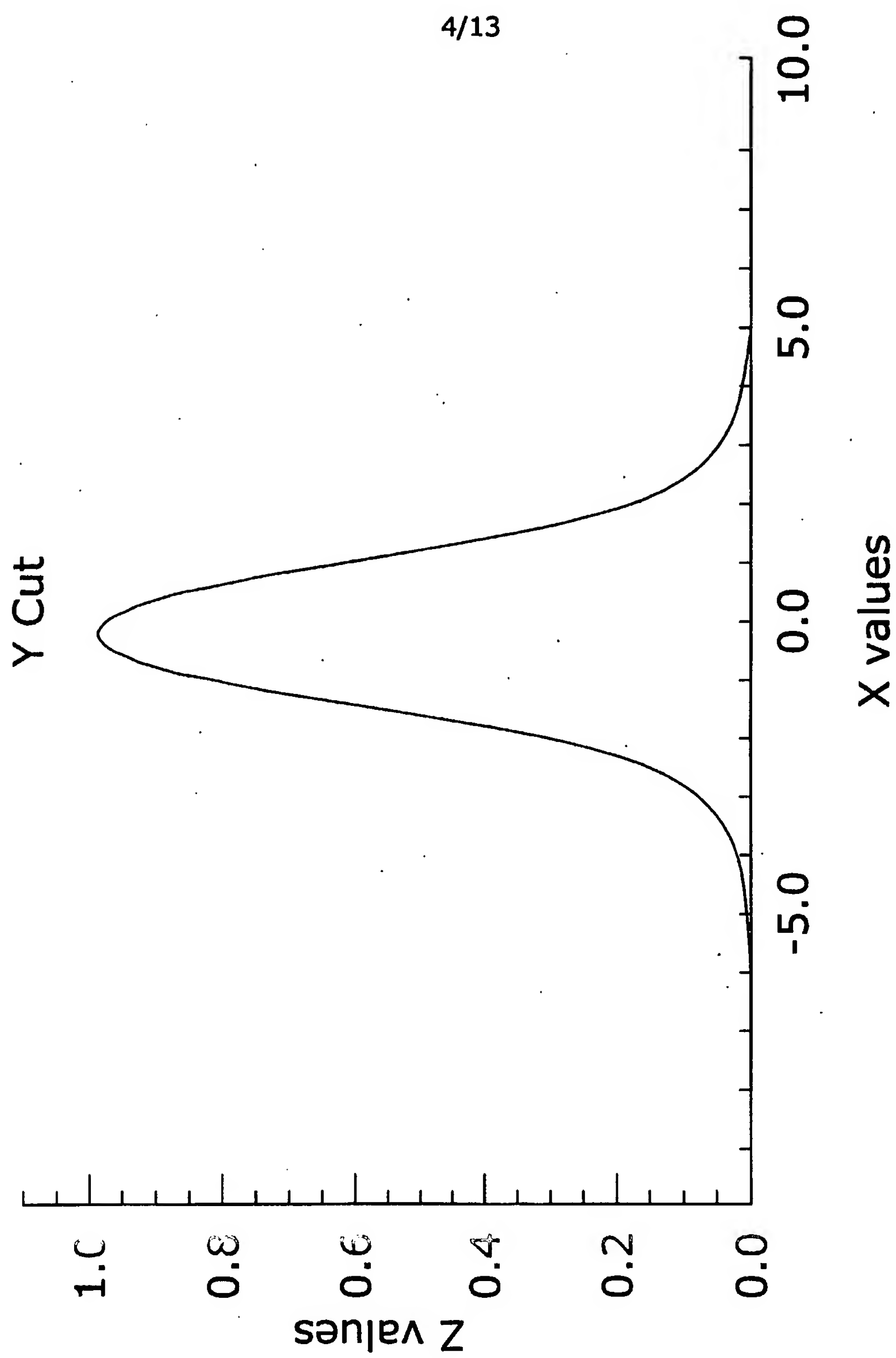
FIG. 3 (a)
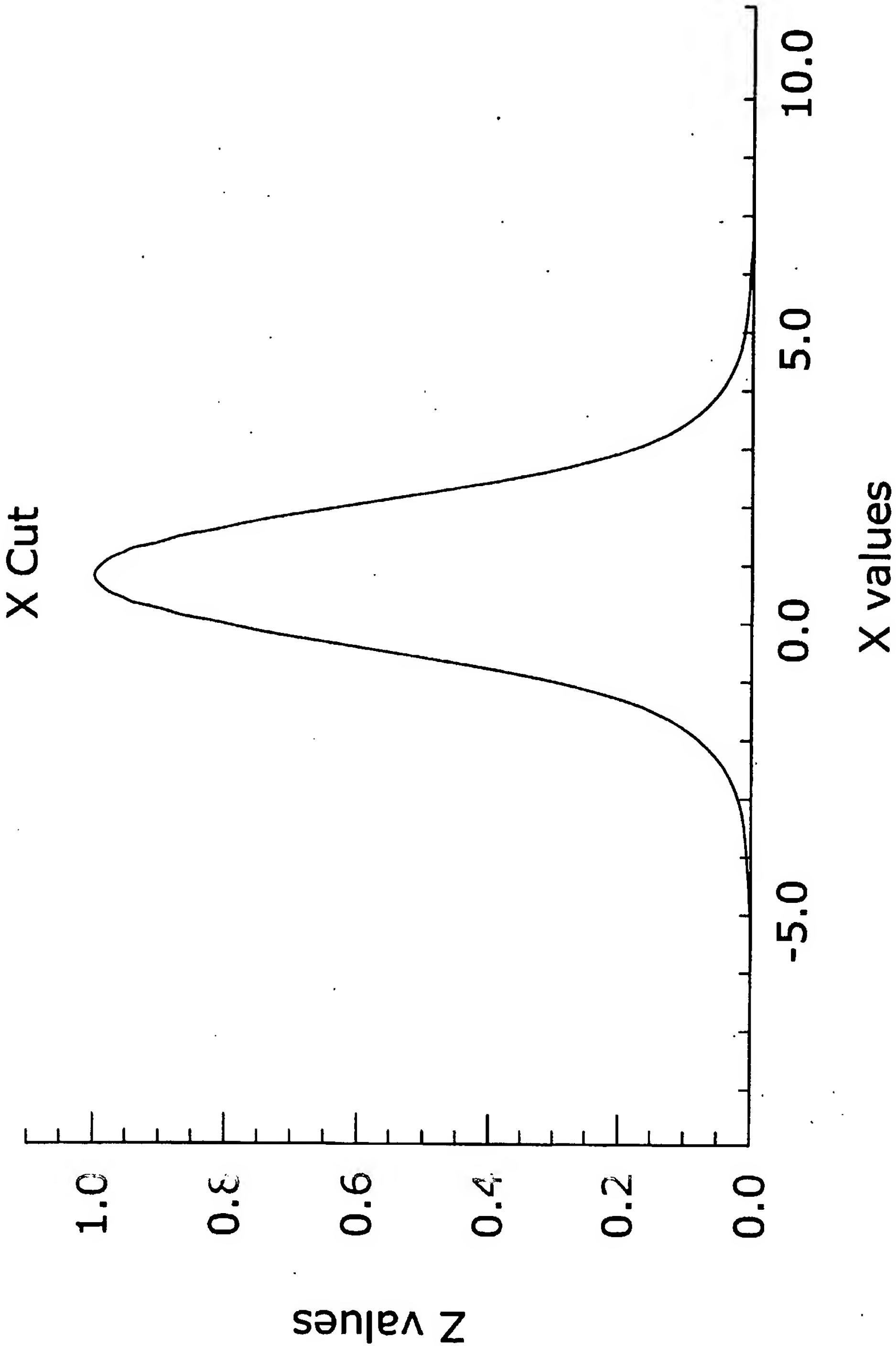
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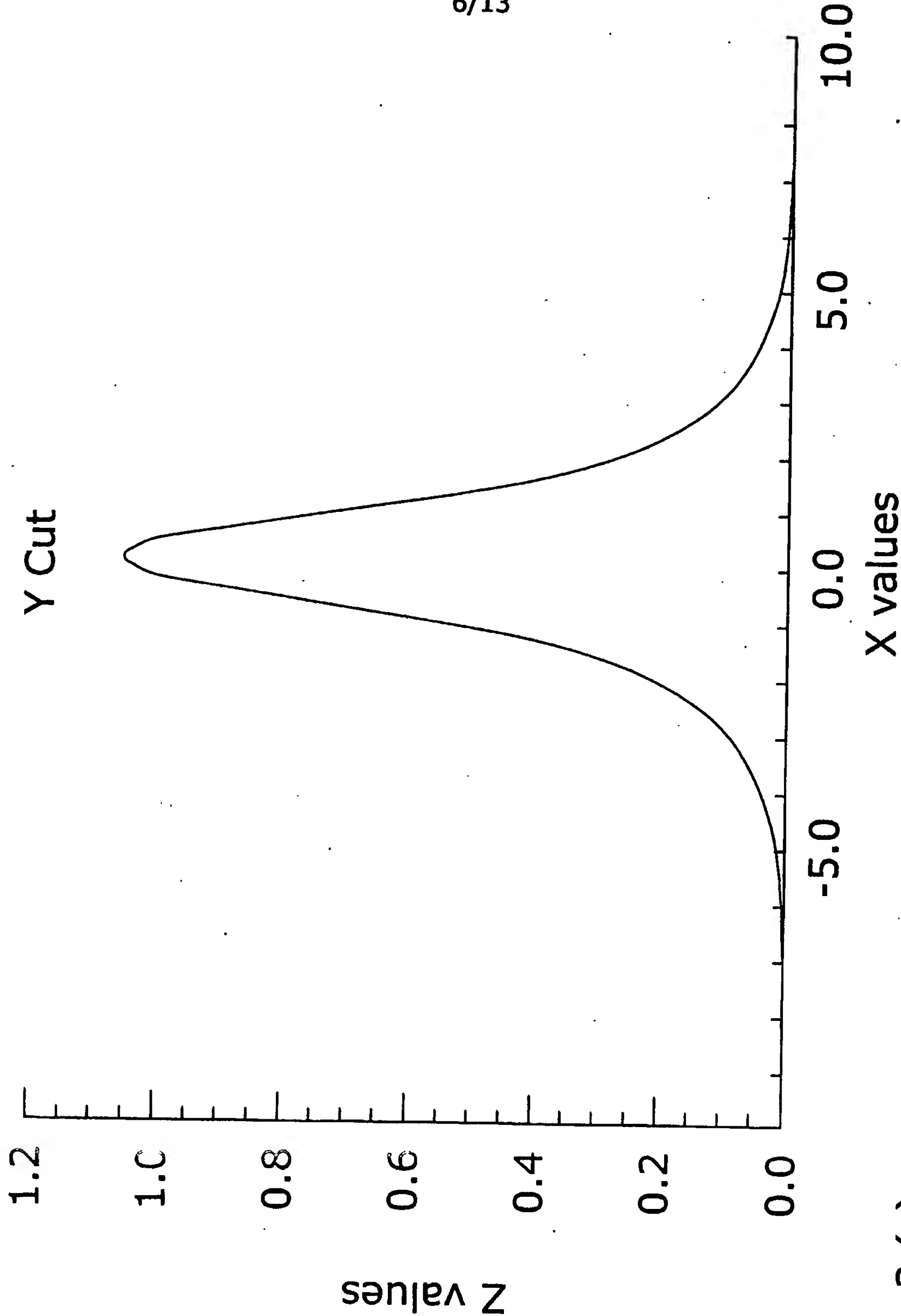
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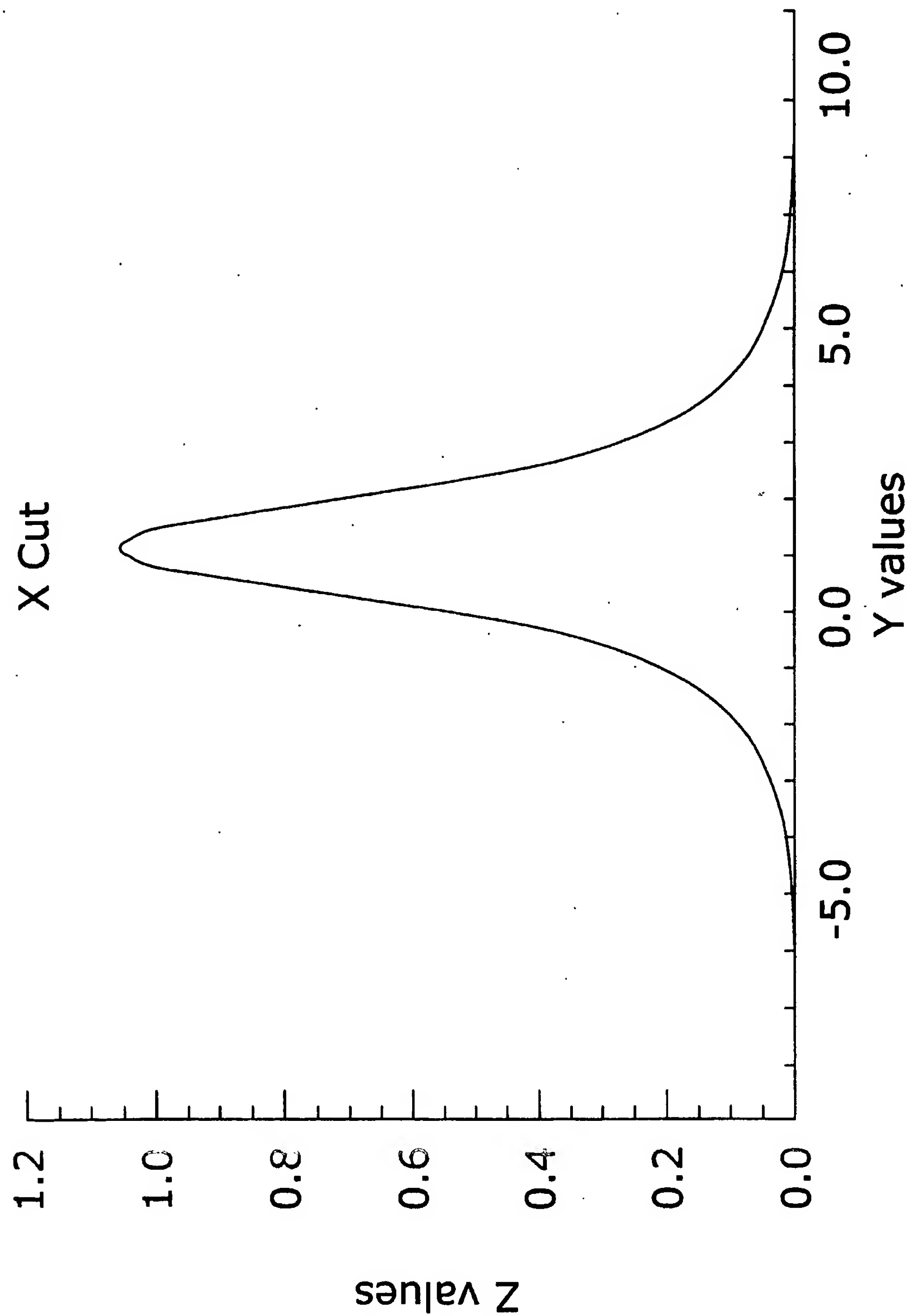
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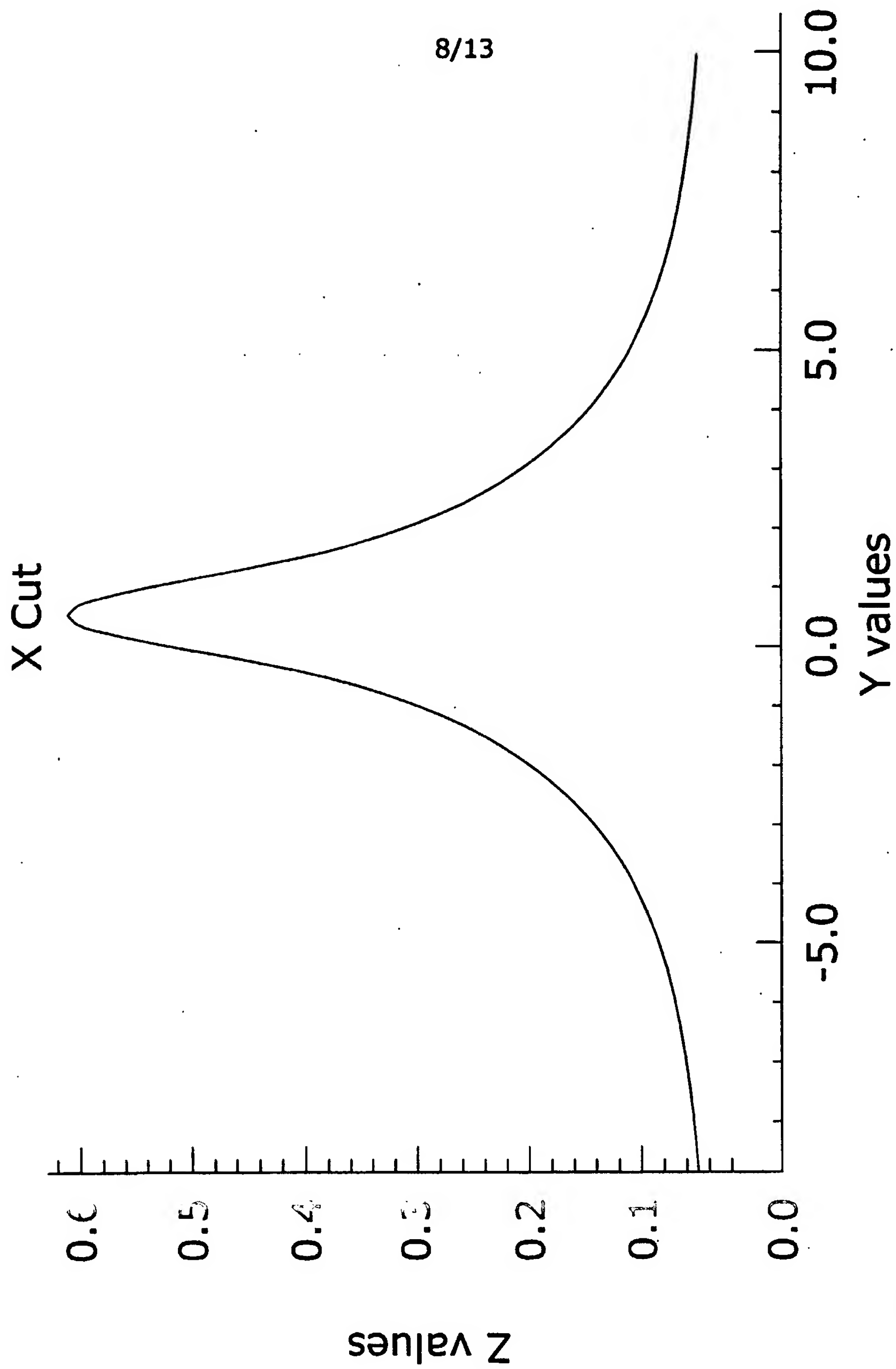
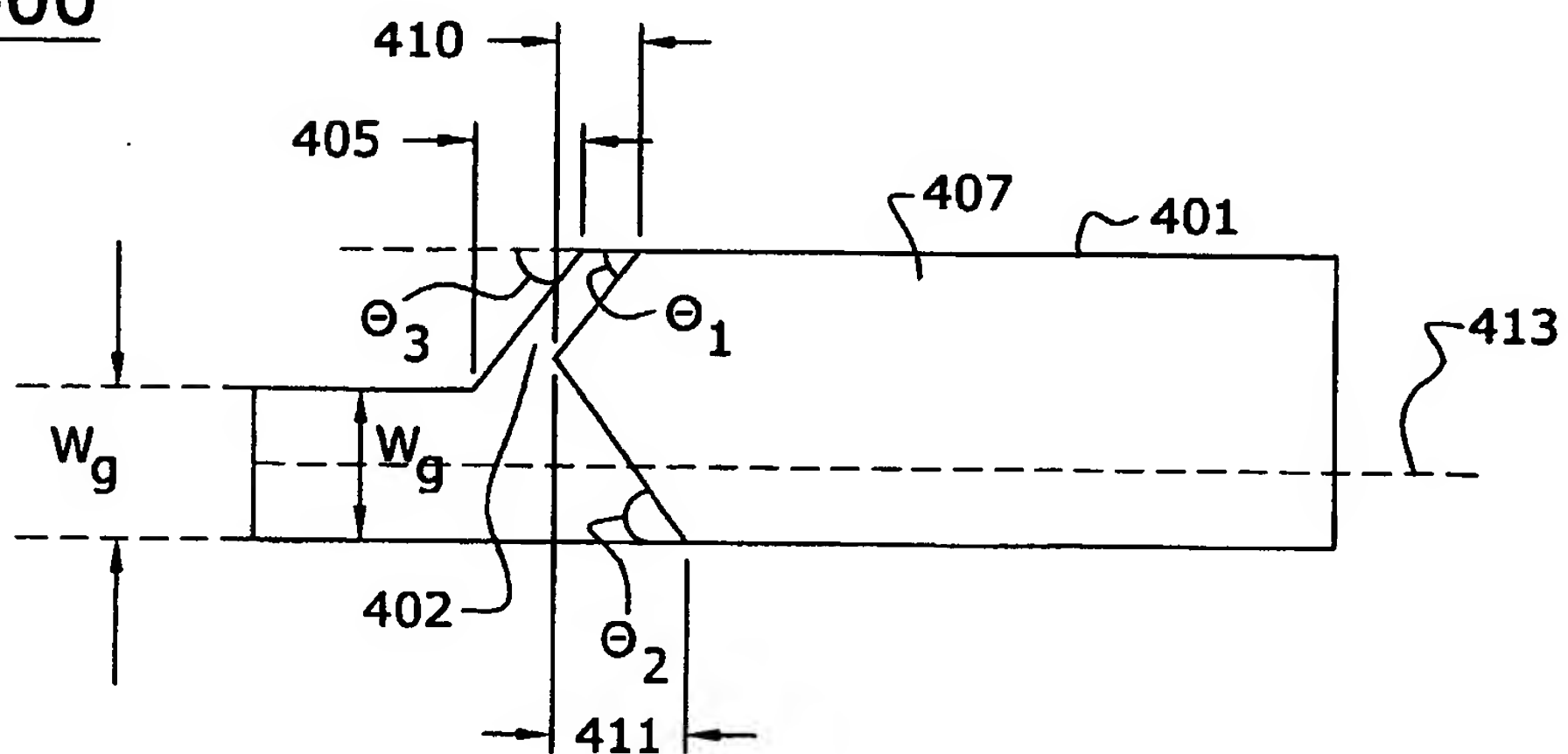FIG. 3 (e)

FIG. 3 (f)

400

FIG. 4 (a)

400

FIG. 4 (b)
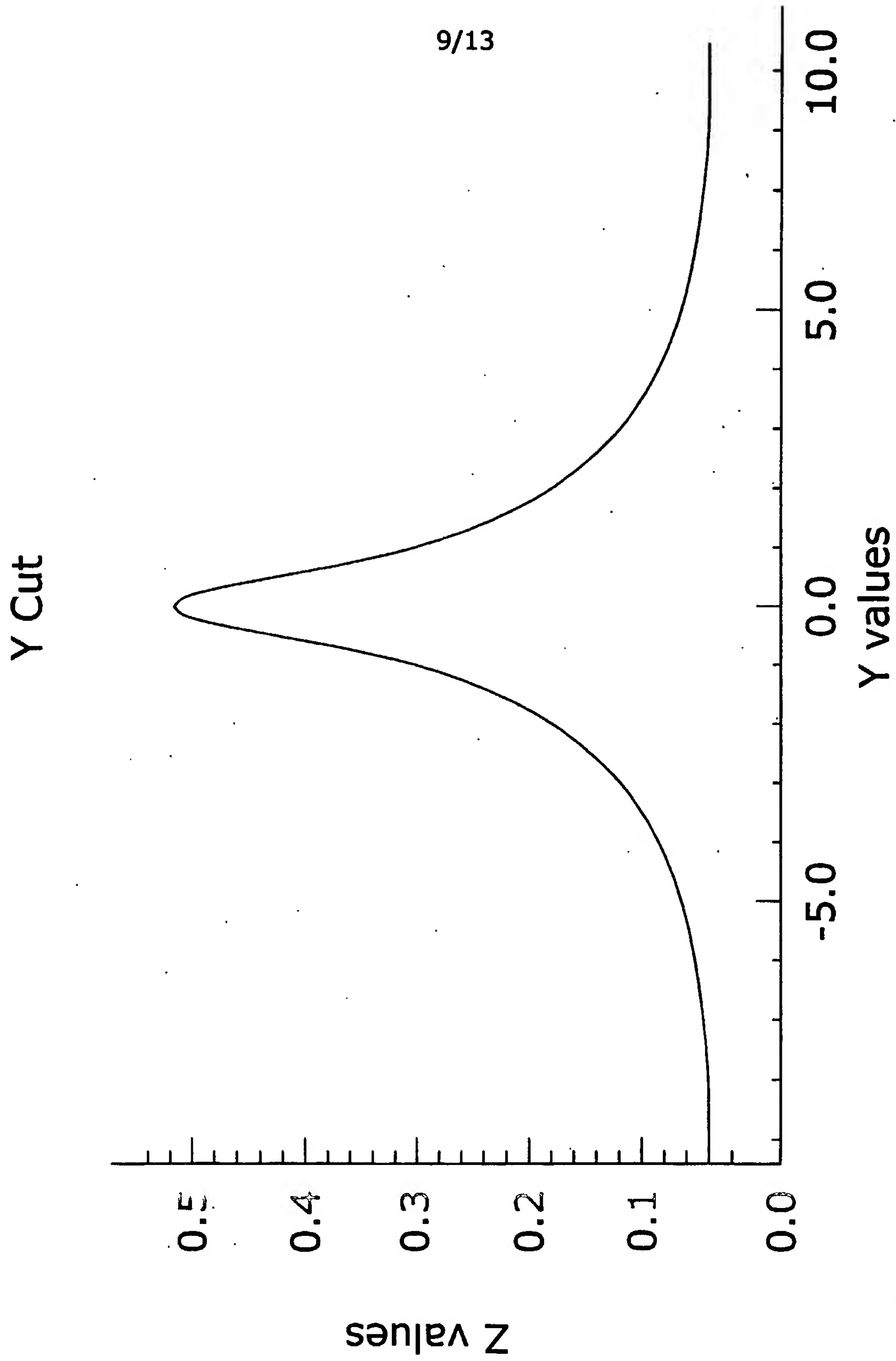
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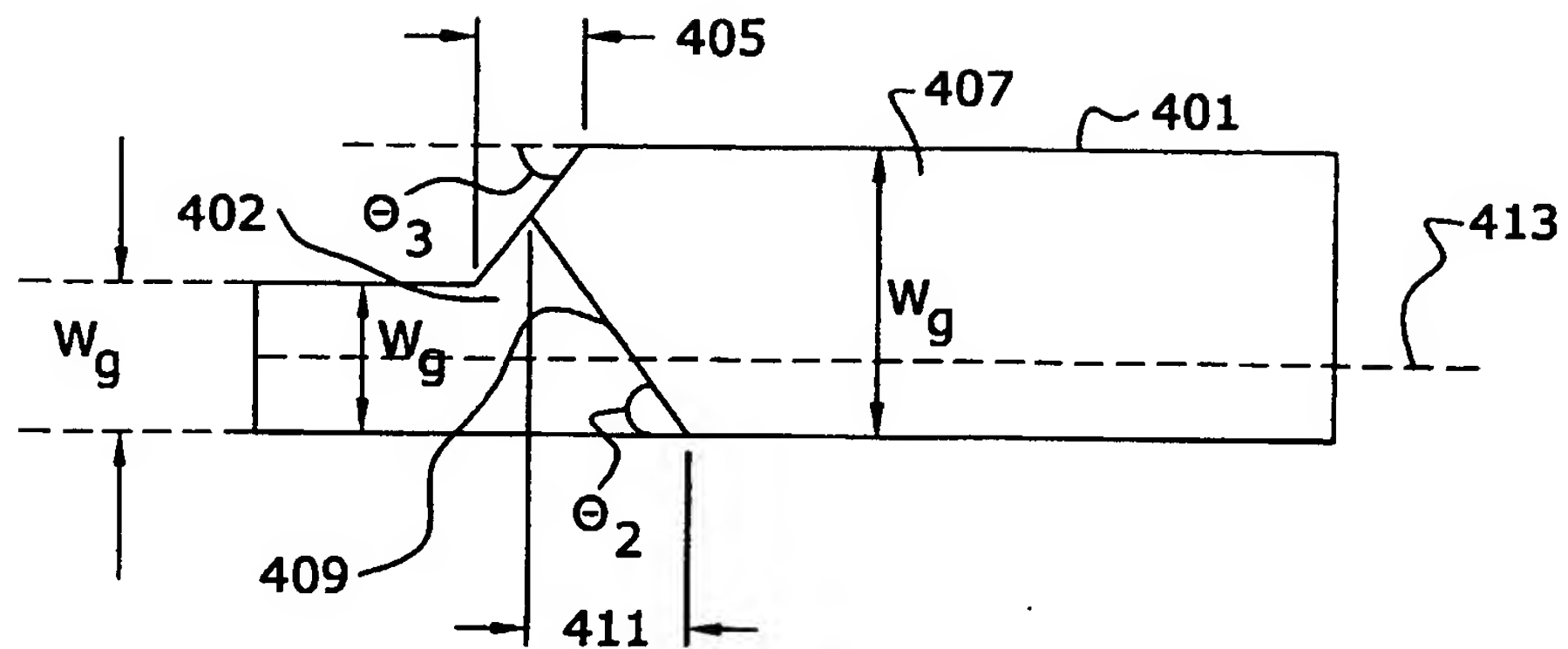
FIG. 4 (c)

400

FIG. 4 (d)

500

FIG. 5

600

FIG. 6